



# Intelligent Engine Systems

## HPT Clearance Control

*General Electric Aviation*  
*Cincinnati, Ohio*

## NASA STI Program . . . in Profile

Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA Scientific and Technical Information (STI) program plays a key part in helping NASA maintain this important role.

The NASA STI Program operates under the auspices of the Agency Chief Information Officer. It collects, organizes, provides for archiving, and disseminates NASA's STI. The NASA STI program provides access to the NASA Aeronautics and Space Database and its public interface, the NASA Technical Reports Server, thus providing one of the largest collections of aeronautical and space science STI in the world. Results are published in both non-NASA channels and by NASA in the NASA STI Report Series, which includes the following report types:

- **TECHNICAL PUBLICATION.** Reports of completed research or a major significant phase of research that present the results of NASA programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA counterpart of peer-reviewed formal professional papers but has less stringent limitations on manuscript length and extent of graphic presentations.
- **TECHNICAL MEMORANDUM.** Scientific and technical findings that are preliminary or of specialized interest, e.g., quick release reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.
- **CONTRACTOR REPORT.** Scientific and technical findings by NASA-sponsored contractors and grantees.
- **CONFERENCE PUBLICATION.** Collected

papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or cosponsored by NASA.

- **SPECIAL PUBLICATION.** Scientific, technical, or historical information from NASA programs, projects, and missions, often concerned with subjects having substantial public interest.
- **TECHNICAL TRANSLATION.** English-language translations of foreign scientific and technical material pertinent to NASA's mission.

Specialized services also include creating custom thesauri, building customized databases, organizing and publishing research results.

For more information about the NASA STI program, see the following:

- Access the NASA STI program home page at <http://www.sti.nasa.gov>
- E-mail your question via the Internet to [help@sti.nasa.gov](mailto:help@sti.nasa.gov)
- Fax your question to the NASA STI Help Desk at 301-621-0134
- Telephone the NASA STI Help Desk at 301-621-0390
- Write to:  
NASA Center for AeroSpace Information (CASI)  
7115 Standard Drive  
Hanover, MD 21076-1320

NASA/CR—2008-215234



# Intelligent Engine Systems

## HPT Clearance Control

*General Electric Aviation  
Cincinnati, Ohio*

Prepared under Contract NAS3-01135, Work element 4.1, Task order 37

National Aeronautics and  
Space Administration

Glenn Research Center  
Cleveland, Ohio 44135

---

June 2008

## Acknowledgments

Prepared by Advanced Mechanical Design.

Trade names and trademarks are used in this report for identification only. Their usage does not constitute an official endorsement, either expressed or implied, by the National Aeronautics and Space Administration.

This work was sponsored by the Fundamental Aeronautics Program at the NASA Glenn Research Center.

*Level of Review:* This material has been technically reviewed by NASA technical management.

Available from

NASA Center for Aerospace Information  
7115 Standard Drive  
Hanover, MD 21076-1320

National Technical Information Service  
5285 Port Royal Road  
Springfield, VA 22161

Available electronically at <http://gltrs.grc.nasa.gov>

# Intelligent Engine Systems

## HPT Clearance Control

General Electric Aviation  
Cincinnati, Ohio 45215

### Objectives

NASA seeks to develop technologies that will enable commercial gas turbine engines to produce fewer emissions and less noise while increasing reliability. Technologies sought lie in the categories of:

- Turbine Engine Prognostics
- Active Controls for Emissions and Noise reduction
- Active Structural Control
- Modeling, Analysis and System Studies

## 1. Technical Progress

### Sub Task 4.1.1

*“After the early clearance probe design and test completion key design and implementation issues were identified for a probe in the extreme HPT environment. This task is to continue the effort to achieve a manufacturable and reliable clearance measurement system.”*

### Sub Task 4.1.2

*“NASA has been working on a mechanically actuated clearance rig in the Mechanical Components Branch at Glenn Research Center (Bruce Steinetz and Shawn Taylor). This year’s plan is to demonstrate SS thermal response including control system capability, positional accuracy, seal leakage and component wear. GE will act in a consulting role for this effort offering guidance in the areas of accuracy requirements, seal/wear issues, and environmental conditions to simulate.”*

### Sub Task 4.1.3

*“To design and analyze advanced thermally activated systems. The goal of such a system would be to tackle the problems associated with current clearance control designs: transient response time, out-of-roundness due to uneven temperature distribution, greater closure capability (“clearance muscle”) and the ability to regenerate new engine clearances in deteriorating engines between overhauls. Also, to continue with the previous effort of compiling data for a scorecard to compare the currently installed systems.”*

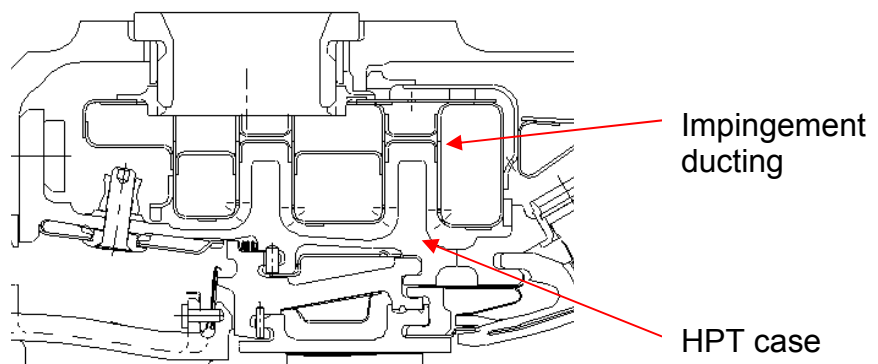
#### 4.1.3b

The Advanced Thermally Actuated Clearance Control System underwent several studies. Improved flow path isolation quantified what can be gained by making the HPT case nearly adiabatic. The best method of heat transfer was established, and finally two different “borrowed” air cooling circuits were evaluated to be used for the HPT Active Clearance Control System.

##### **Improved flow-path isolation**

An area of study in the advanced thermally controlled systems field is the following work exploring improvement in thermal isolation of the casing from the hot gas flow. A study by Phil Dong and Amid Ansari examines the current design with a case of ideal insulation.

A current CF34-10 thermally controlled system utilizes sheet metal ducting carrying 4<sup>th</sup> and 9<sup>th</sup> stage compressor bleed air to Active Clearance Control (ACC) rings. Figure 4.1.3b.1 below shows this system. The ducting is perforated in the area close to the base of the ACC rings, for impinging the ACC air on the ring base.



**Figure 4.1.3b.1 CF34-10 HPT case and ACC system**

Using the combination of 4<sup>th</sup> and 9<sup>th</sup> stage bleed air the rings are cooled in order to close the clearance between the shrouds and High Pressure Turbine blades.

The current configuration of shielding the hot gas flows underneath the casing was analyzed as the base line for the study. As is shown in Fig. 4.1.3b.4, three heat shields are installed on the inside of the case, FWD, MID, and AFT heat shields.

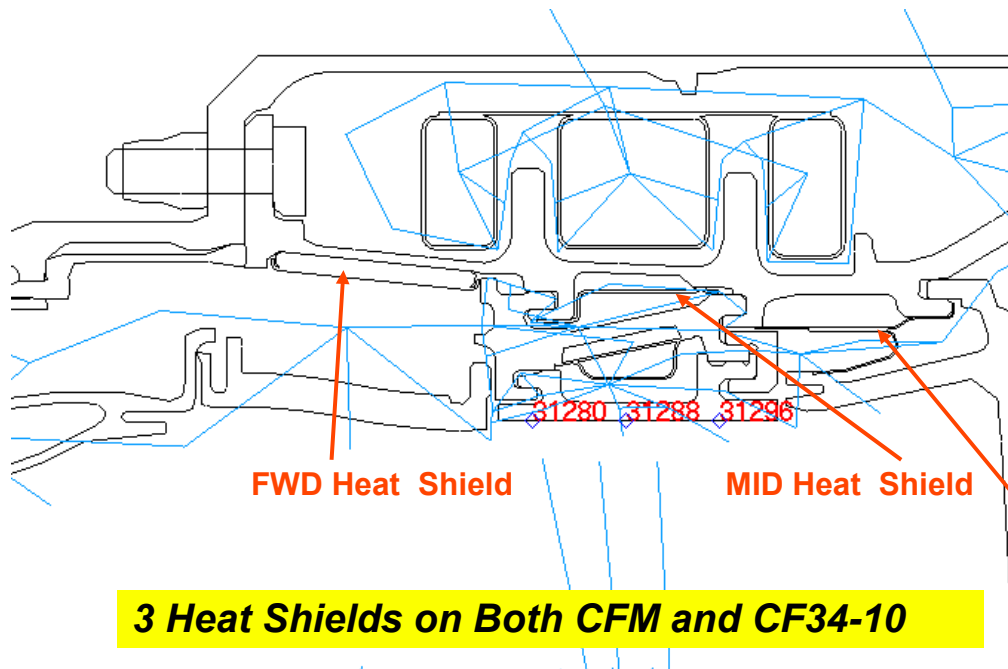


Figure 4.1.3b.4 P/thermal model representing the heat shields and the surrounding flows

The forward heat shield consists of a sheet metal cover containing a honeycomb structure between it and the casing. The other two are sheet metal partitions, which prevent the compressor discharge-temperature to flow and directly heat the case. To study possible improvements of thermal isolation, a nearly ideally thermally isolated case was studied and compared to the baseline current set-up. A very low heat transfer coefficient of 2 Btu / hr ft<sup>2</sup> F was used for the analysis on case inboard surfaces.

The results of the study are best summarized as an increase in “clearance muscle”, or the ability of the system to close clearances. Cruise is traditionally the part of the mission when tightest clearances are maintained. The improved isolation would allow closing the clearance at cruise by approximately 0.002”.

## **Perforated Ring Studies**

The goal of the ACC design is, when desirable, to maximize the amount of heat extracted from the Clearance Control Rings (or pseudo-flanges), while minimizing pressure loss through the system and ensuring good controllability. Current state of art systems concentrate on cruise as it's the most stable part of a mission. The ideal system would allow to "dial in" necessary clearance at all portions of the mission – idle, take off, climb, cruise and descent. Current slow thermal systems try to match the behavior of the disk to that of the case. The ACC systems are focused on maintaining the case round and closing cruise clearance to raise HPT efficiency. The limit for how far the HPT clearance can be set is in part set by the protection against a rub for a burst from cruise to max power. This clearance protection is eliminated or reduced, in theory, with a fast thermal system. The fast acting system allows tighter clearances over the entire flight and including descent, where the schedule has been significantly more open due to protection against rubs during a reburst to max power. Fuel savings due to higher HPT efficiency could be achieved in climb, cruise and descent. Significant improvements could be seen in short flights where climb and descent make up the majority of the mission.

Three different ACC designs were evaluated. First is a system similar to current impingement schemes. As experience shows the most effective current systems utilize impingement on lower part of the ring, hence such a system is included (4.1.3b.6). The other two systems have been studied, but never used in production. These methods employ an array of holes in the Clearance Control rings. The ACC air is routed through these holes maximizing convective heat transfer on the surface of these holes into the ACC rings. Two variations of this system are in the air flow-path route. One scheme introduces the ACC air into a cavity between FWD ring and combustor casing flange (4.1.3b.7). The air is then routed through holes in both rings in series and extracted from a cavity created between the AFT ring and another wall. The second layout introduces the ACC air into the cavity between the two rings and splits the flow between the rings. The air moves through the holes in the two rings in parallel and to the cavities on either side of the ring where it would leave the ACC system (4.1.3b.8).

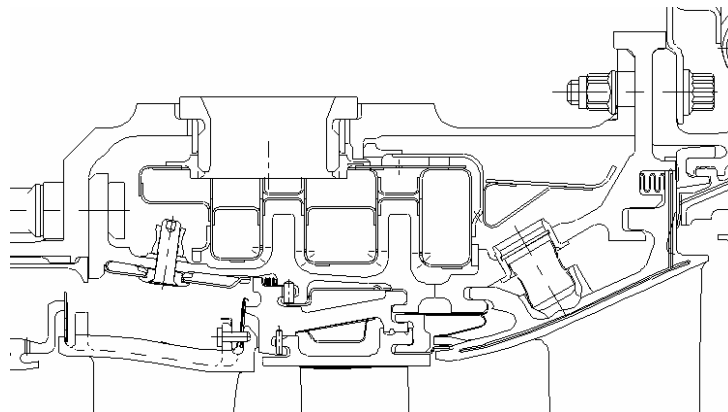




Figure 4.1.3b.6 CFM56 impingement system

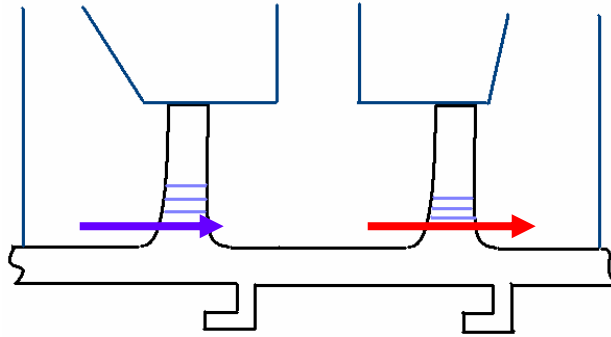


Figure 4.1.3b.8 Parallel flow perforated rings system

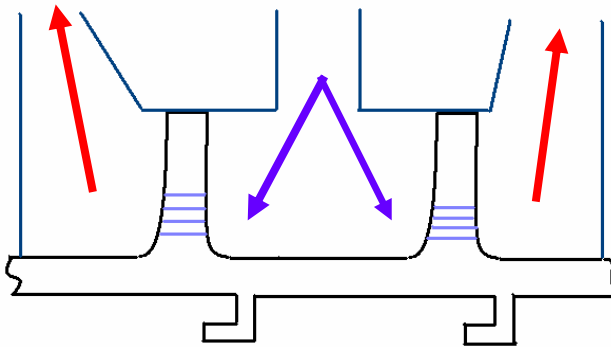


Figure 4.1.3b.9 Perforated rings - air pumped into middle cavity

The convection schemes were evaluated and the best system was selected and further optimized. The study conducted for the selection of the system used accepted calculations derived from empirical data match of convective heat transfer. The Nusselt Number and the heat transfer coefficient (htc), which are dependent on the type of flow, were calculated using the below presented equations. The locations of each of the flow assumptions are presented further.

$$h = \frac{Nu * k}{Dh}$$

A) Flat plate

$$Nu = 0.037 * (Re^{0.8} - Re^{0.4}) * (Pr^{0.33})$$

Where:

Nu – Nusselt number

h – heat transfer coefficient

Re – Reynolds number

Pr – Prandtl number

k – thermal conductivity

Dh – hydraulic diameter

Xn – distance between holes

Xent – entrance corrective factor length

B) Impingement (array - Kerchner)

$$Nu = 2.0 * (Re^m) * ((Xn/Dh)^{-2.0}) * (Pr^{.33})$$

C) Backwash

$$Nu = 0.6 * 2.0 * (Re^m) * ((Xn/Dh)^{-2.0}) * (Pr^{.33})$$

D) Ductflow

$$Nu = 0.023 * (Re^{0.88}) * (Pr^{.33}) * (1 + 1.2 * Dh/X_{ent})$$

The three systems evaluated were: current impingement ACC system using 0.02" and 0.03" diameter holes, and four variations of the perforated rings set-up. The perforated rings were assessed in 2 diameter sizes - 0.03" and 0.04". The two drilling configurations studied, using both sizes, were parallel with the axis, as well as using a 60° angle of inclination. The angle provides twice the length and surface area inside of the holes, as well as introduces partially circumferential flow in the exit cavity increasing velocities on ring walls and case. A manufacturing specialist estimated the angle of 60° as maximum achievable in the thickness of the ACC rings. The hole size was also limited to 0.03" diameter due to material thickness.

To evaluate the merit of each system the comparison variable used was  $htc * area$  ( $hA$ ). Assumed were 2% W25 flow and an equal pressure drop across every system. The specific areas used to calculate the heat transfer into the rings and case, are presented below in figures 4.1.3b.10 – 4.1.3b.12.

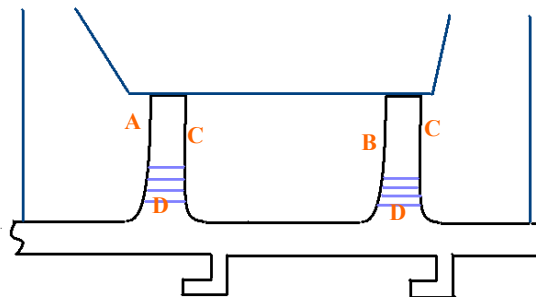
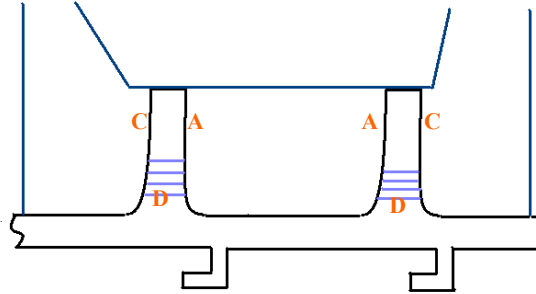
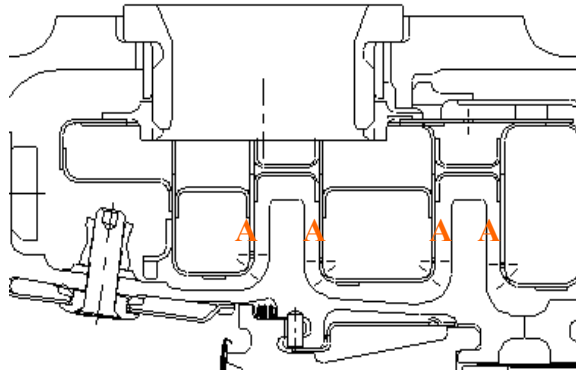


Figure 4.1.3b.10 In-series flow through rings calculation of heat flow



**Figure 4.1.3b.11 Parallel flow through rings calculation of heat flow**



**Figure 4.1.3b.12 Current impingement calculation of heat flow into rings**

The results of this study are presented on the plots presented in fig 4.1.3b.13 and 4.1.3b.14. There are two bars provided for each in-series result because the convection mechanisms aren't symmetric like in the parallel setup.

- 0.03" impingement manifold
- 0.02" impingement manifold (today's system)
- 0.04" perpendicularly perforated ring parallel flow through rings
- 0.03" perpendicularly perforated ring parallel flow through rings
- 0.04" perpendicularly perforated ring series flow through rings
- 0.03" perpendicularly perforated ring series flow through rings

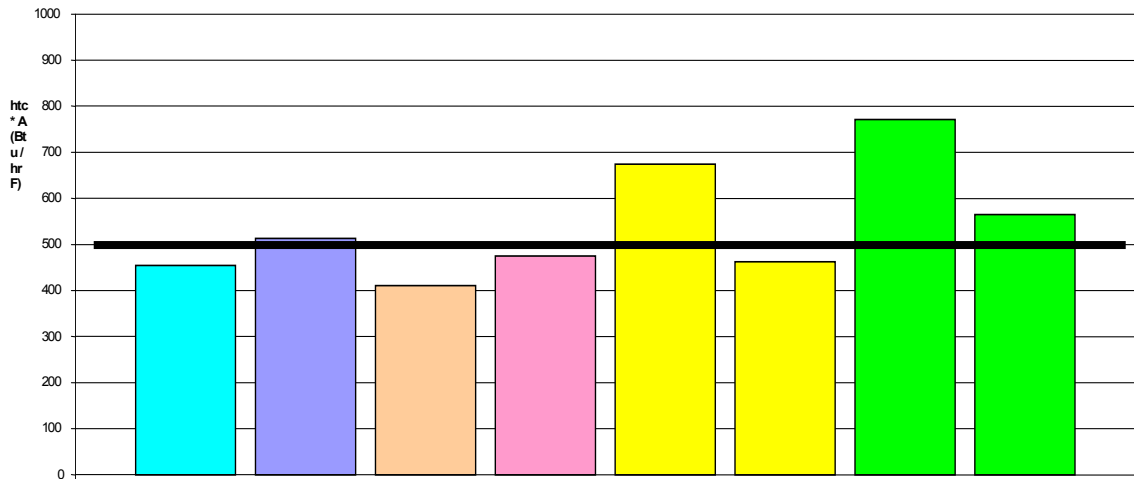


Figure 4.1.3b.13 h\*A results: impingement and perforated rings with perpendicular holes

- 0.03" impingement manifold
- 0.02" impingement manifold (today's system)
- 0.04" 60° perforated ring parallel flow through rings
- 0.03" 60° perforated ring parallel flow through rings
- 0.04" 60° perforated ring series flow through rings
- 0.03" 60° perforated ring series flow through rings

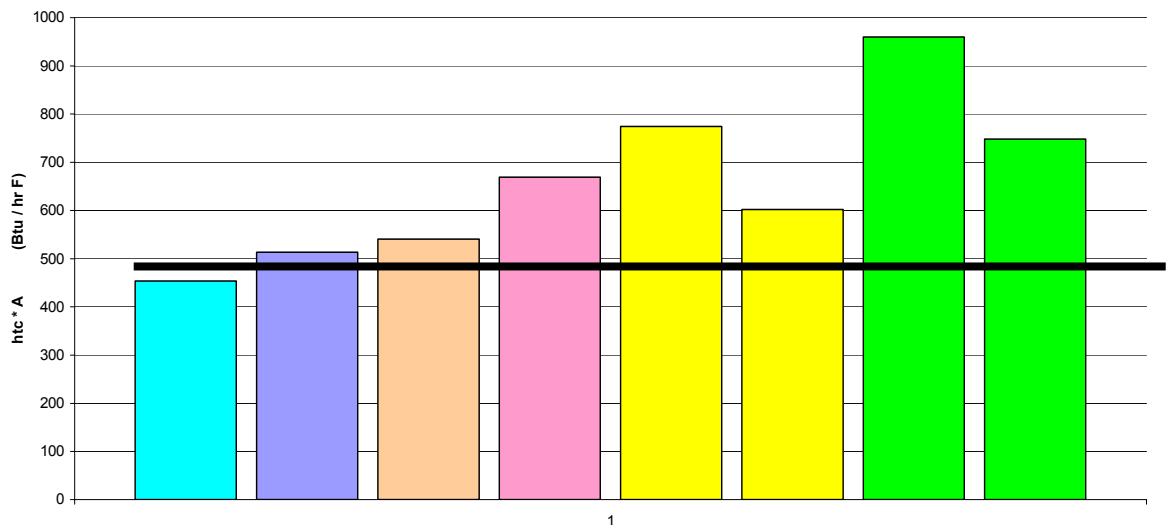


Figure 4.1.3b.14 h\*A results: impingement and perforated ring with 60 deg inclined holes

The system that provides the best ability to absorb heat from the ACC air is on fig. 4.1.3b.14 represented by green bars. The  $h^*A$  value studied is nearly 70% (both rings averaged) larger than today's system would deliver at the same flow. Hence the in-series, perforated at  $60^\circ$ , 0.03" diameter hole design was chosen as the new HPT case configuration.

Several hole patterns were tested to find the most efficient one that fits the envelope allocated on the ACC ring. A 2-D FEA axisymmetric model was constructed and used in the study. The different arrangements were represented as orthotropic material properties. The two patterns showing greatest difference are presented below in Figures 4.1.3b.16 and 17. As it can be seen the difference is minor at less than 0.002" at 5 seconds into the maneuver, concluding that within the same perforated area the differences in the pattern are minor.

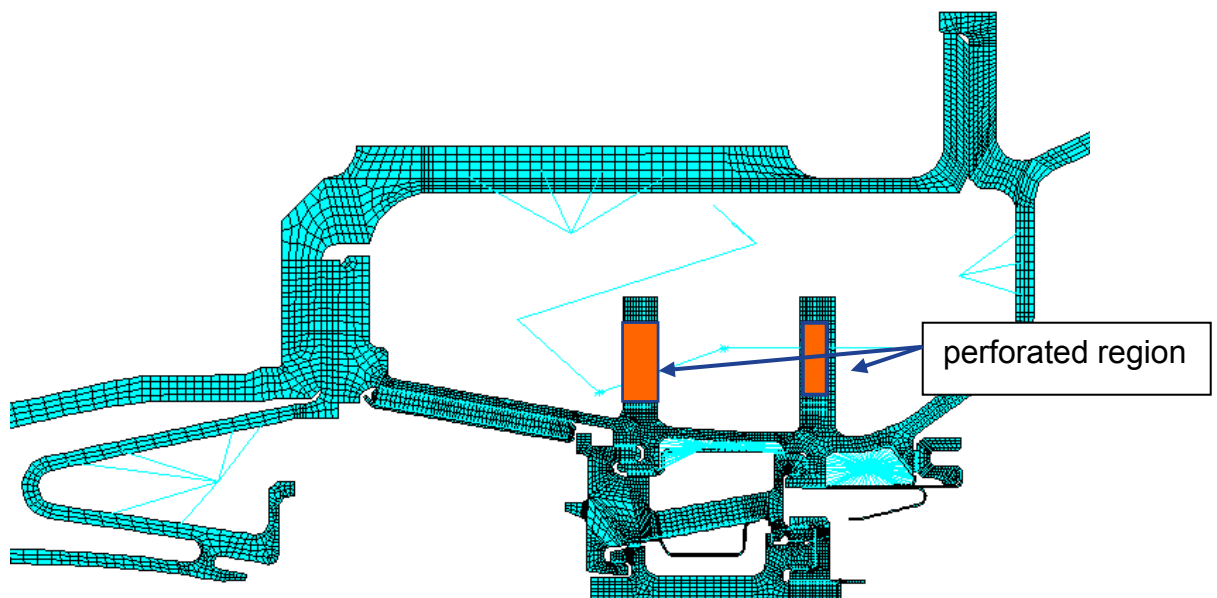
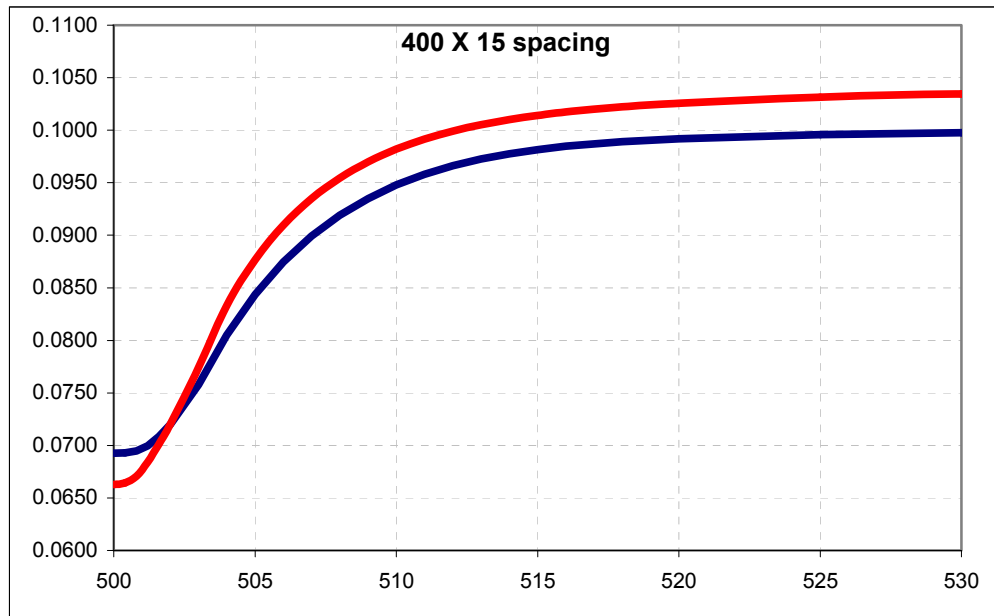
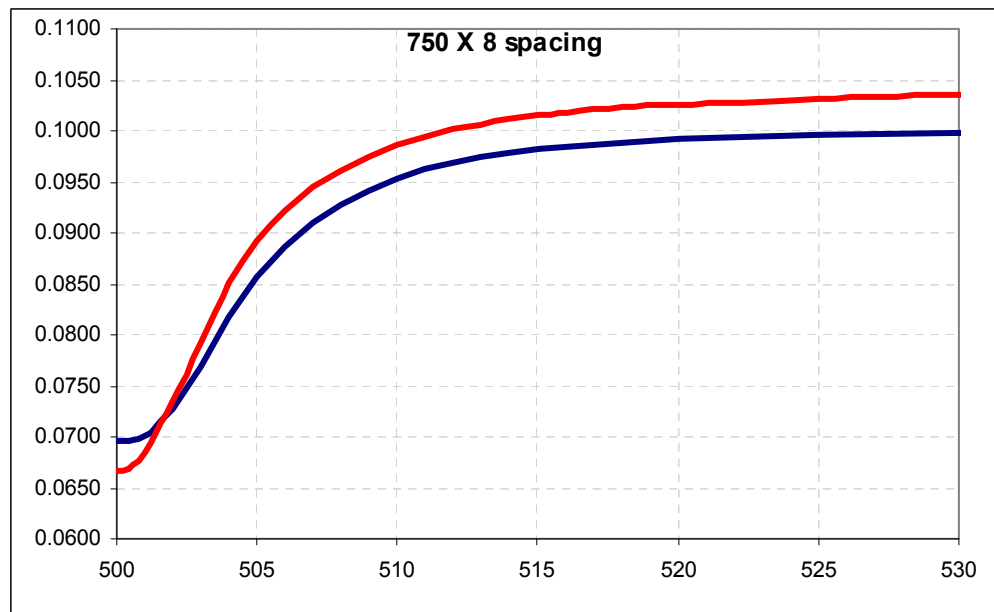


Figure 4.1.3b.15 ANSYS model used in hole arrangement study



**Figure 4.1.3b.16 400 columns in 15 rows transient case response at the hooks**



**Figure 4.1.3b.17 750 columns in 8 rows transient case response at the hooks**

## Cooled Cooling Air and HPT Active Clearance Control

In the area of advanced thermal systems a combined system of Cooled Compressor Discharge Active Clearance Control and HPT Blade Cooling Air concept was designed and analyzed. The general idea is to use a fan air cooled compressor discharge air in Clearance Control and High Pressure Turbine (HPT) blade cooling. Such an ACC system would provide a significantly faster thermal response of the HPT casing due to the quality of the air used. This concept was founded on two previous studies conducted at GE. One quantified the ACC ring thermal response versus the pressure and temperature of air used. Another studied the air flow savings that could be realized by decreasing temperature of HPT blade cooling air.

To provide an overview of such a system a schematic (4.1.3b.18) is used.

Compressor discharge (CD) air is extracted through ports, similar to customer bleed (1). Depending on the schedule of ACC, the air is routed to either Active Clearance Control (ACC) (2) or through a heat exchanger located in fan airflow path (3). The heat exchanger bypass (2) is needed for the  $T_3$  air to act in ACC during pinch points in the mission. The other route, through the heat exchanger (3), provides air approximately 350F cooler than compressor discharge ( $T_3 - 350F$ ). From the heat exchanger (4) the air travels through valves to either the ACC section of the system (6) or is bypassed into the HPT cooling application (5). In the ACC the air acts on rings located on the casing over the HPT. These rings either heated (CD air –no cooling (2)) or cooled (heat exchanger (4)) provide a means of setting a desired HPT clearance.

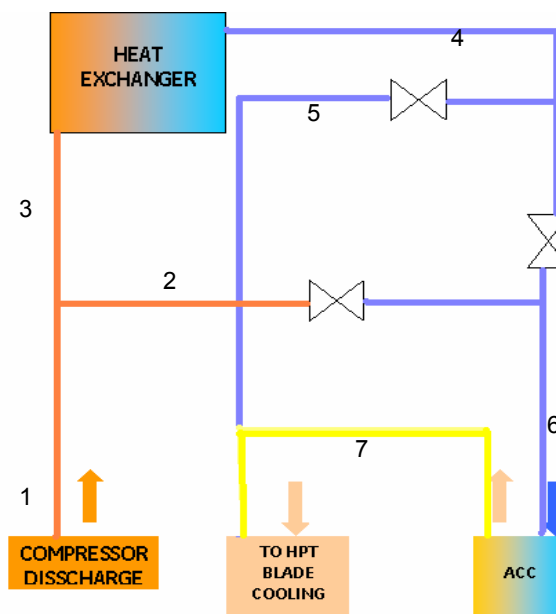
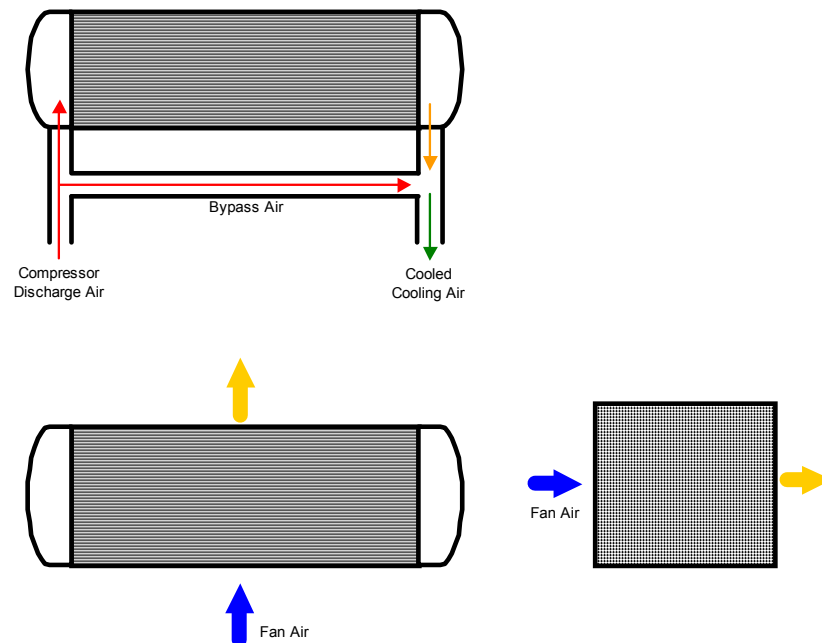


Figure 4.1.3b.18 CD ACC and CA schematic

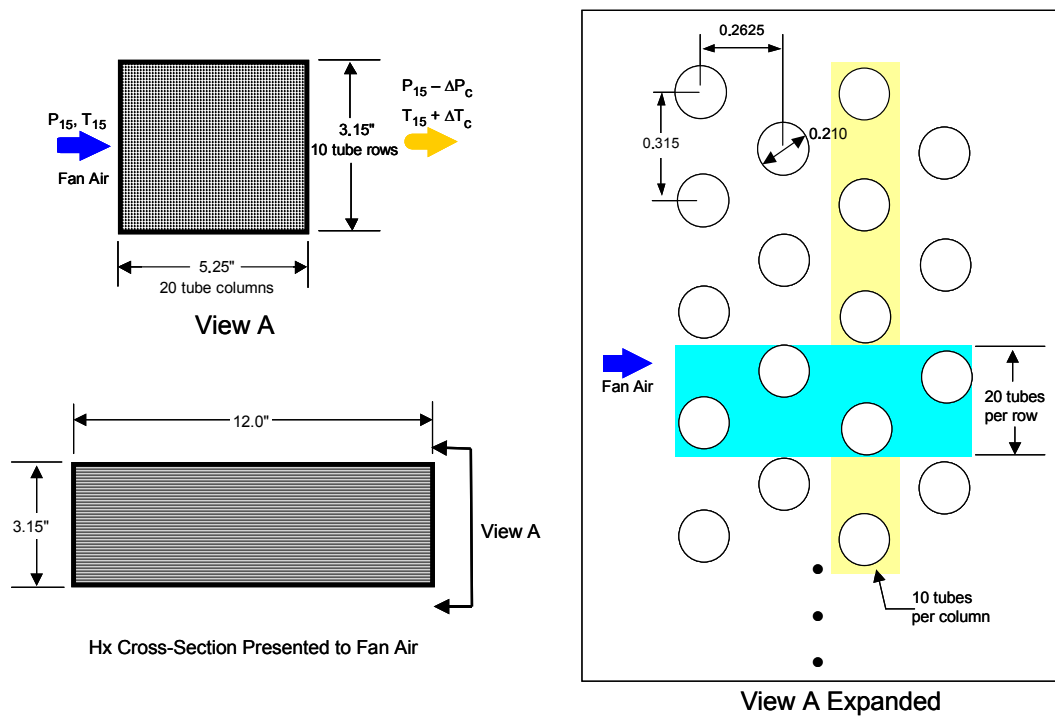
The spent clearance control air (7) is combined with ACC bypass air and mixed in a cavity under the combustor inner liner then routed through the inducer to provide HPT blade cooling.

Another part of the system necessary to bring the study to completion was the heat exchanger design. An air-to-air heat exchanger was designed to be placed in a scoop protruding radially inward from the fan air flowpath. The single pass exchanger carries compressor discharge (cooled) air in tubes and fan air passing outside tubes. A continuous bypass is provided to mix heat exchanger cooled air with bypass air to provide desirable output temperature as not to overcool the cooling air. The 200 tube exchanger was designed to be made of Inconel-625 and weigh 5.7 lbs. As it can be seen from fig. 4.1.3b.21 the heat exchanger compressor discharge air produces a drop of approximately 270F during climb and cruise. These are the parts of the mission where the most benefit from the muscle derived from the difference in temperatures can be realized.



**Figure 4.1.3b.19 Air to air heat exchanger design overview**





T Taylor, [jimothy.w.taylor@ae.ge.com](mailto:jimothy.w.taylor@ae.ge.com), (513) 243-6946

Figure 4.1.3b.20 Air to air heat exchanger design details

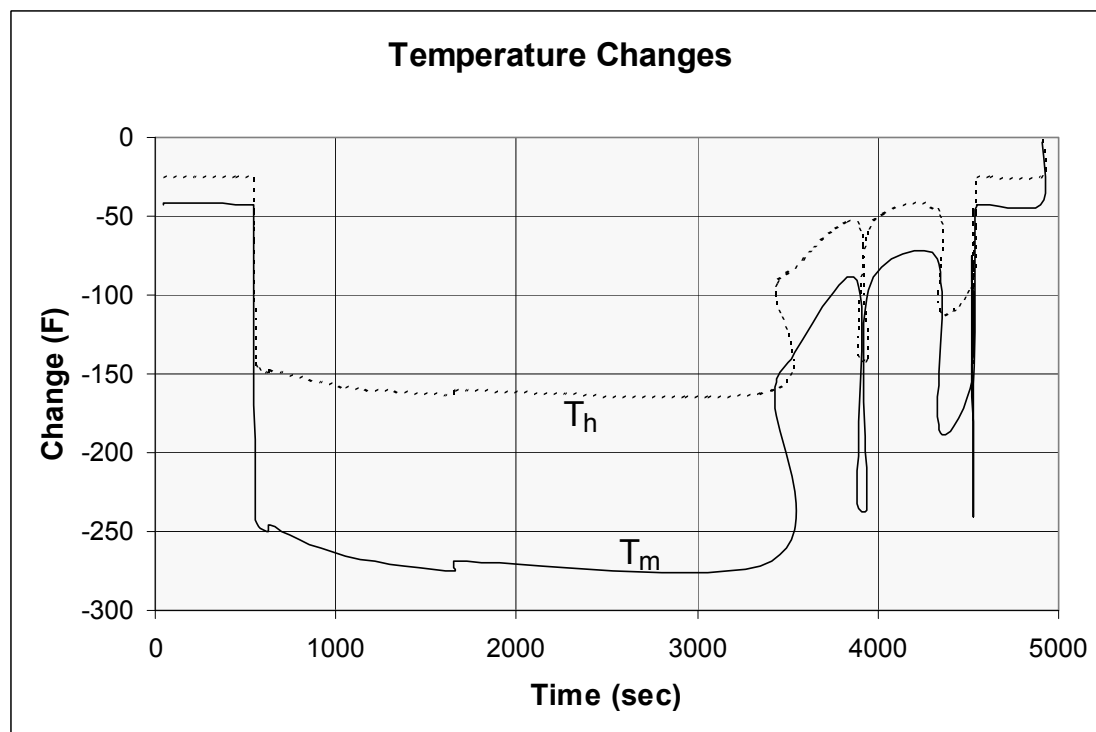


Figure 4.1.3b.21 Heat exchanger output presented as change in compressor discharge temperature during the studied mission.

The system studied was evaluated using the CFM56-5 ACC system as a comparative base. One of the goals of this system was to eliminate rub protection added to today's cruise clearance by speeding up the reaction time during a step climb engine speed change. This was realized as the case was deflected (using an FEA model) about 0.010" at the end of the maneuver, exceeding the blade tip expansion of 0.005" – 0.007" (depending on engine). The system also gained about 0.007" of range, or "muscle", as shown in plot 4.1.3b.23. This muscle can be used to close down HPT clearance as the engine deteriorates. From investigation, it was found that the "extra muscle" is not enough to maintain new engine HPT clearance throughout engine life.

Another benefit of this system is its behavior during a take-off transient. The take-off pinch point (HPT clearance closes down to a minimum value) occurs as the engine increases in speed and flow path in temperature. Next, there is a period where the clearance opens as the slower reacting case absorbs heat. Finally, the disk, with its slowest thermal time constant, closes the clearance aided by the ACC system. Contrasting to that is what happens during this period to a fast acting case. Very little peak and valley can be seen during the take-off pinch point period. As air to ACC is increased, during the subsequent opening, HPT clearance is being actively managed.

This system requires blade cooling air to be delivered to the blade externally via the heat exchanger and ACC system. Depending on application returning this flow to a cavity from which the blade cooling air can be drawn may be an obstacle. Another impracticality, less definable in hard numbers, is the added density and complexity of piping, valves and system controls typically referred to as clutter (see Figure 4.1.3b.26).

The goal, on the clearance side, was to design a system that has a much greater range and speed of actuation through a wide range source air temperatures. On the blade cooling side of the system, the goal was to reduce the amount of cooling air without introducing more thermal stress into the blade. During the study it was found that these are competing needs. The temperature difference needed to optimize the ACC system (~350F) is too great for the blade cooling side of the system. The heat exchanger was sized to deliver the right temperature cooling air to the blade (-)270F. While this scheme surpasses the current state of art systems in both speed and range, it falls short of the previously set goal of 0.010" of extra cruise muscle.

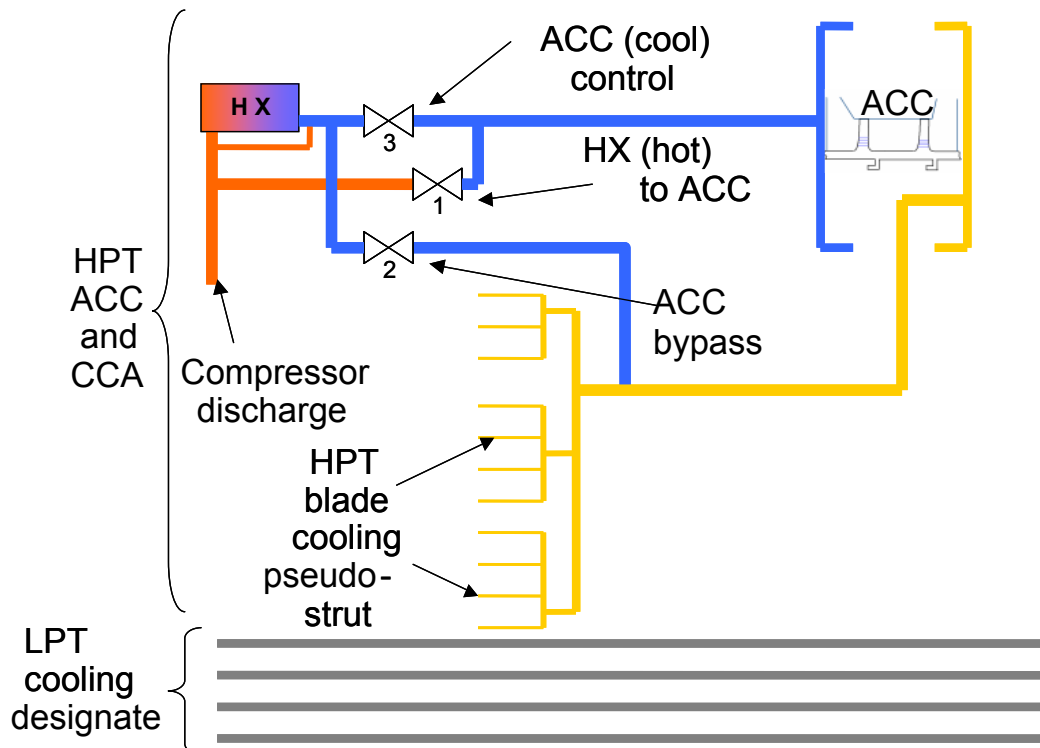


Figure 4.1.3b.26 System piping

### LPT cooling air based ACC system

As the Cooled Cooling Air and HPT Active Clearance Control system failed to meet all expectations, and the piping diagram looked impractical, work moved to a less complex system. As a second variation of the fast thermal system the currently employed CFM56 Low Power Turbine cooling air and ACC circuit was considered.

Downselected earlier, the heat transfer method of the perforated ring is applied unchanged to this variant to minimize the system's time constant.

Using the LPT cooling circuit presented its own challenges. Limitations are placed on the pressure drop across the system as the sink pressure of this circuit is proportional to the source pressure. Increasing the hole count to maintain a margin became necessary. To act as a fast system this system needed a flow in the order of 2%W25, as well as a significant temperature difference between air sources. The circuit considered offered about 50 F of temperature difference more than the Cooled Cooling Air circuit. In order to meet all the requirements of the entire cooling circuit including the downstream destination had to be analyzed.

This system was modeled using 1-D fluid software to ensure the entire range of flows meets the needs of the rest of the system, based on Figure 4.1.3b.14. The modes of operation designed into the system were:

- no ACC flow – all flow through bypass and LPT designated
- modulated mid-compressor bleed flow to ACC – other flow balanced to maintain circuit flow level through ACC bypass and designated
- max mid-compressor bleed through ACC – balance through LPT designated
- max compressor discharge through ACC – balance through LPT designated

In particular the ACC flow was scrutinized during the cruise to climb step change in engine speed (last mode above). The disk and blades stretch mechanically and the blades grow rapidly thermally during this maneuver. The ACC system would switch from one of the first three normal modes to the fourth to compensate for the blade tip growth. This mode uses compressor discharge which, after throttling, is 2-3% higher in pressure than the rest of the system. This allows to flow more cooling air through the ACC system and maintain same flow into the downstream cooling circuit. This “hot” air is initially at cruise power compressor discharge temperature and as the engine gains speed, it changes to climb power compressor discharge temperature.

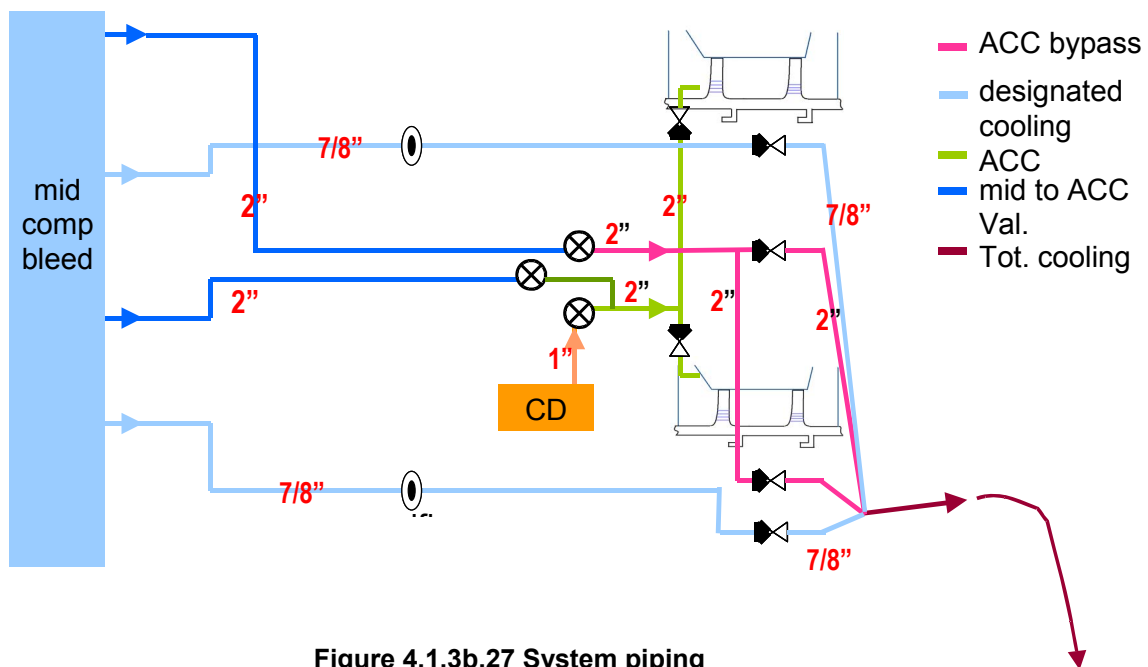


Figure 4.1.3b.27 System piping

After designing the circuit its capability was tested using a 2-D axisymmetric FEA model (Figure 4.1.3b.15). The most important transient maneuver was tested – the cruise to climb speed change. This is when the fast response is necessary. The piping, as well as the air temperature and pressure were given lags based on engine data, as the cycle changes. This model was further optimized by using different hole arrangements and the results are presented in Figures 4.1.3b.16 and

17. The two extremes of hole placement produced very similar results of 0.016" at the end of the maneuver. As only 0.005"-0.008" (depending on engine) are needed to compensate for the speed change it is sufficient to satisfy this requirement. The second requirement of increasing the ACC system range to account for future deterioration is more difficult to achieve. Taller ACC rings have been designed to provide more "muscle" and compensate for the necessary removal of ring material during drilling. The results of these changes fall short of the initially set goals of 0.010" of extra range, by adding 0.002". This, however, may be improved by exploring further the fast acting system through optimizing the ACC flow schedule and cold built clearance.

REPORT DOCUMENTATION PAGE			Form Approved OMB No. 0704-0188	
<p>The public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.</p> <p>PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.</p>				
1. REPORT DATE (DD-MM-YYYY) 01-06-2008		2. REPORT TYPE Final Contractor Report		3. DATES COVERED (From - To) April 2005-June 2006
4. TITLE AND SUBTITLE Intelligent Engine Systems HPT Clearance Control			5a. CONTRACT NUMBER NAS3-01135	
			5b. GRANT NUMBER	
			5c. PROGRAM ELEMENT NUMBER 4.1	
6. AUTHOR(S) Aviation, General Electric			5d. PROJECT NUMBER	
			5e. TASK NUMBER 37	
			5f. WORK UNIT NUMBER WBS 984754.02.07.03.11.03	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) General Electric Aircraft Engines One Neumann Way Cincinnati, Ohio 45215			8. PERFORMING ORGANIZATION REPORT NUMBER E-16493	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) National Aeronautics and Space Administration Washington, DC 20546-0001			10. SPONSORING/MONITORS ACRONYM(S) NASA	
			11. SPONSORING/MONITORING REPORT NUMBER NASA/CR-2008-215234	
12. DISTRIBUTION/AVAILABILITY STATEMENT Unclassified-Unlimited Subject Category: 07 Available electronically at <a href="http://gltrs.grc.nasa.gov">http://gltrs.grc.nasa.gov</a> This publication is available from the NASA Center for AeroSpace Information, 301-621-0390				
13. SUPPLEMENTARY NOTES				
14. ABSTRACT The Advanced Thermally Actuated Clearance Control System underwent several studies. Improved flow path isolation quantified what can be gained by making the HPT case nearly adiabatic. The best method of heat transfer was established, and finally two different "borrowed" air cooling circuits were evaluated to be used for the HPT Active Clearance Control System.				
15. SUBJECT TERMS Gas turbine engines; Turbines; Actuators for aircraft				
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT  UU	18. NUMBER OF PAGES 23
a. REPORT U	b. ABSTRACT U	c. THIS PAGE U		
				19b. TELEPHONE NUMBER (include area code) 301-621-0390



